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Report AMCA-70-001

AERIAL VERY HEAVY LIFT CONCEPTS FOR THE 1990 ARMY

VOLUME I - BASIC REPORT

Ad Hoc Working Group No. 6

November 1969

Final Report

U.S. ARMY
ADVANCED MATERIEL CONCEPTS AGENCY

Report AMCA-70-001

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ABSTRACT

An Ad Hoc Working Group (AHWG) was convened by the US Army Advanced Materiel Concepts Agency (AMCA) to consider the technical feasibility of developing a very heavy aerial lift vehicle to be operational by 1990. The mission spectrum for such a vehicle was assumed similar to the proposed QMR for the heavy-lift helicopter except for the payload requirement which was increased in these considerations to approximately 50-60 tons. Shaft-driven and tip-driven helicopter concepts were given major consideration. Powerplant and transmission development and problems relating to subsystems, such as load handling and control, were treated. Vertical take-off and landing (VTOL) concepts that were not high disc loading were discussed. Short take-off and landing (STOL) was not considered.

The principal conclusions reached by the Ad Hoc Working Group are listed below.

- A very-heavy-lift helicopter (VHLH), either shaft-driven or tip-driven, is technically feasible today and could be type classified by 1985.

- Excessive coning and droop appear to be the major technical problems in the development of a VHLH.

- Turbo-shaft conversions of existing turbojet engines suitable for the VHLH could be available within three to five years, depending on funding.

- A modified lighter-than-air vehicle augmented with dynamic lift and lifting thrusters is a plausible concept.

PREFACE

An AHWG was convened by AMCA on 20-22 May 1969. Participants included representatives of the Government (DOD, NASA, and DOT), industry, and academic communities. The members of the AHWG, with names and affiliation, are listed in Section IX of this report.

Expertise was available in the areas of military operations, helicopter technology, propulsion, V/STOL aircraft, and lighter-than-air vehicles. The first half of the three-day meeting was devoted to prepared briefings in these areas. The material presented in these briefings can be found in Volumes II and III of this report.

Following the briefings, the AHWG was divided into five subcommittees to consider (1) shaft-driven helicopters, (2) tip-driven helicopters, (3) VTOL configurations other than helicopters, (4) powerplants and transmissions, and (5) subsystems. The findings of these subgroups form the basis for the body of this report, recommendations and conclusions. These are taken both from the report of each subgroup and from the general discussion in the plenary AHWG discussions which ensued from the subgroup's report.

The US Army Advanced Materiel Concepts Agency acknowledges the valuable contribution of Dr. Barnes McCormick, Head of the Department of Aerospace Engineering at Penn State University, who served as Chairman of the AHWG and assisted in the preparation of this report. In addition, a sincere thank-you is given to all participants and in particular to the chairmen of the subcommittees--Mr. Bernard Lindenbaum, Dr. Henry R. Velkoff, Mr. Robert B. Bossler, Jr., Mr. Edward S. Carter, and Mr. W. Z. Stepniewski. A complete list of participants is contained in Section IX of this report.

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SECTION I
PURPOSE, BACKGROUND, AND SCOPE

1. Purpose.

The purpose of this study was to examine potential aerial very heavy lift (VHL) concepts capable of lifting 50 to 60 tons of payload vertically from unprepared areas in the 1990 time frame.

2. Background.

Airmobility has become a significant influence on tactical operations on the battlefield. Through the use of aircraft in Southeast Asia (SEA), both fixed-wing and rotary-wing, airmobile operations have grown in the areas of observation, troop transport, direct fire support, and cargo lift. In this last area--cargo lift--the helicopter has emerged as the work horse of the Army. With such aircraft as the UH-1, CH-47, and CH-54, the Army has the capability of lifting various sized cargo internally and externally, from small loads, measured in pounds, up to bulky and out-sized loads of 12-13 tons. The use of such aircraft for movement of artillery has enhanced the battlefield balance of power by allowing the ground force commander to quickly and efficiently place and fire artillery under his command; recover downed and damaged aircraft to an extent that the savings of the aircraft recovered has exceeded the cost of the rescuing aircraft; and facilitate replenishment of bulk supplies to ground units.

Due to these successful operations in SEA, as well as recent HLH R&D efforts in the USSR, high level Army and DOD interest is calling for development of a heavy lift capability with a payload of 20+ tons. With this additional capability it will be possible to lift the great majority of the equipment used by the Army, with the exceptions being the main battle tank (MBT), self-propelled artillery, some heavy construction equipment, and certain missile systems.

Late in 1968, in a meeting attended by the Commanding Generals of the US Army Materiel Command and US Army Combat Developments Command, the technical feasibility of a 50-60 ton heavy lift development program was discussed. During that meeting, General Besson stated that the Army must consider concepts for obtaining greater lift capability concurrently with the HLH development program then in progress. At the present time there is no on-going developmental work in the field of very heavy lift, and there has been very little consideration of solutions which involve any item other than helicopters.

The field of heavy lift is one in which the USSR appears to have a definite lead on the US. For a number of years, they have been

actively engaged in an R&D effort in this area. In early 1969, the USSR lifted over 34 tons with a helicopter to an altitude of more than 9,000 feet. They are now claiming four world heavy lift helicopter records in 15, 20, 25, and 30 ton weight categories at an altitude of 9,000 feet. Unofficial information indicates that they are presently developing a very heavy lift helicopter of payload in excess of 50 tons.

This AHWG directly addressed two USACDC's Institute of Land Combat functional objectives which state broad requirements for the Army of 1990. They are: (1) "transport men and materiel within a hostile land environment by air vehicles," and (2) "transport specially shaped, bulky, heavy, peculiarly configured items of equipment, in an assembled, operating configuration, without disassembling for ease in shipment." Additionally, a VHL vehicle offers a considerable capability in achieving the objective to move men and materiel from the sea onto a hostile shore by water/air vehicles, to including overcoming barriers and obstacles in the area of ship-to-shore discharge of large quantities of cargo. It also has possibility of fulfilling another functional objective--"evacuate abandoned, damaged, salvaged, and captured materiel from the battle zone, requiring only minimum security from tactical units."

3. The AHWG Objectives.

a. To examine very heavy lift concepts capable of lifting payloads in the 50-60 ton area in the 1990 time frame.

b. To document the technical feasibility and the operational practicability of each concept.

c. To identify the technological constraints which exist for each concept with a view to stating what is required now in the way of R&D effort.

d. To identify priority approaches which should be pursued by the Army in order to obtain a very heavy lift capability for the Army of 1990.

4. Scope.

The AHWG examined both existing and plausible new approaches to the solution of the problem. Included was an examination of the various types of helicopters which may be capable of accomplishing the task (e.g., shaft-driven, hot cycle, and other gas reaction drive types). Also considered were future V/STOL aircraft, lighter-than-air vehicles (dirigibles and blimps), flexible wing vehicles, gliders, load sharing techniques utilizing two or more aerial platforms, and other schemes suggested by participants.

At the initiation of the AHWC, a review was made of the DOD R&D effort in the area of heavy lift, with emphasis on the current Army Heavy Lift Helicopter Program. A representative of the Intelligence community made a classified presentation on foreign heavy lift technology (Volume II). A representative of Combat Developments Command (CDC) discussed the requirements for a very heavy lift aerial vehicle in the post 1985 time frame. Other presentations provided background for subsequent discussions (Volume III).

The problem was addressed from both the technical and operational viewpoint. Each proposed solution was discussed separately. An in-depth examination of the characteristics and major subsystems of each approach was made in order to determine technological problems and gaps which exist. Similarly, the operational practicability and the restraints to effective utilization in the field of each concept was discussed and documented.

Each problem area associated with each concept proposed was examined and documented. Suggested courses of R&D effort to either overcome these problems or determine the plausibility of the concept were recommended. It is envisioned that, as a result of such effort, a subsequent determination can be made as to whether or not to continue with the conceptual R&D effort. No attempt was made to gain a consensus of the participants as to a preferential rating of the alternative conceptual approaches.

SECTION II
SHAFT-DRIVEN HELICOPTER

The approach taken was to identify the important areas involved in developing and using a shaft-driven very heavy lift helicopter and to show the technological problems which exist and need to be solved. While no specific assessment was made of the possibility of developing a 50-ton payload vehicle by 1990, consensus indicated that there was little doubt that this could be done, essentially with existing technology and adequate funding. Applications of new materials, improvement in analytical techniques and methods, better understanding of certain phenomena, and a number of test efforts were considered necessary, however, to allow design and construction of such aircraft on a reasonable risk basis.

The configurations which were considered were the single rotor, the co-axial, the synchropter, the tandem, the lateral twin, the tri-rotor and the quad-rotor. Although primary emphasis was placed on the single rotor, most of the problems which are outlined below as requiring further study apply to all of the configurations.

1. The Basic Design of the VHL Helicopter.

The helicopter, as a flying crane, will be capable of carrying heavy loads which are aerodynamically dirty, at modest speeds, for small distances. However, without its payload, the drag and weight of the helicopter are reduced appreciably, while its available power remains the same. One should design the helicopter to exploit this difference in operating conditions. Early in the development cycle of the machine, consideration should be given to other likely uses, since these could influence the design itself and the quantity produced, and make for better justification of acquisition cost. Civil uses, as well as military, should be considered.

2. Stabilization.

Redundant fly-by-wire control systems providing artificial stability can eliminate the need for additional stabilizing surfaces.

3. Disc Loading.

Current practice is not to exceed a disc loading of 10 psf. What should the limit be for the VHL? If lower, there are serious implications on the weight and size. If higher, there are savings in weight and size, but there are also downwash problems. The downwash problems should be investigated in the field with different disc loadings before the disc loading for the VHL is fixed.

4. Noise.

Today's requirements are not really sufficiently definitive. Detectability and annoyance are quite different problems. Both, from a perceived noise standpoint (PNDB), are in need of further study. This is particularly true for a rotor producing an impulsive type of noise commonly referred to as blade "slap" or "bang." In this regard more basic work is needed to understand the mechanism which generates this noise. A study of the expected vortex geometry and core size for the VHLH should be made.

5. Autorotational Capability.

Is the Army's requirement of autorotational capability for the flying crane necessary on a multi-engine aircraft? This requirement affects the design appreciably, particularly for higher disc loadings. Consideration should be given to eliminating it and relying instead on multi-engine reliability and capability. The major rebuttal to any proposed elimination of the requirements centers on the loss of the transmission. This leads to the need for the design of a transmission which will not seize if lubrication is lost.

6. Rotor Design.

There appears to be a lack of knowledge to accomplish the optimization of the rotor design, including considerations of such items as noise, hover efficiency, vibrations, blade loads, and hub loads. We need a better understanding of the aerodynamics of the rotor system, particularly with regard to the relationship between blade geometry and production of tip vortices. For very large blades,consideration should be given to means of control other than feathering the inboard end. This might include aerodynamic control systems such as circulation control by blowing, or leading edge slots and trailing edge flaps. In addition, consideration should be given to the merits of controllable twist by the use of outboard segment feathering.

The problems of excessive droop and coning of large rotors must be given attention. This is aggravated, in the case of coning, by the proposed application of new, lighter materials. Higher tip speeds will help in this regard; and so, airfoils which yield them should be studied. These airfoils should now, however, sacrifice lifting performance in hover. The application of new fibrous materials to rotor blade construction raises problems with regard to the attendant lack of structural damping. If the blade is structured to introduce more damping, fatigue life may be affected. Naturally, blade design must be examined not only on a strength-to-weight basis but also from a damping and fatigue life standpoint.

7. Hub Design.

Classically, articulated rotors have been attached to the hub through ball and roller bearings. Continued attention should be given to the use of flexures, in particular the elastomeric type. This is not to imply that work should be abandoned on other means of attaining flapping and lead and lag motions, such as the uniball system or lighter ball and roller bearings employing hollow spheres and cylinders.

8. Test Facilities.

Attention must be given to the development of new national test facilities for developing and proofing of very large rotors of the order of 150 ft. and greater in diameter. A whirl tower capable of performing hover tests both in and out of ground effect is needed. Also, some type of facility will be needed for simulating aerodynamic and dynamic behavior in forward flight. Dynamic modeling must be used extensively in the development of these much larger but relatively lighter rotors.

9. Dynamics.

The fundamental blade passage frequency of the very-large-diameter rotors will be lower than that of present day rotors unless larger numbers of blades are used on the larger rotors. The lower driving frequencies could result in both ground and air resonance problems. In addition to structural dynamic problems, the lower disturbance frequencies could prove very annoying to the crew and passengers.

The gust response of large rotors may become an important problem in terms of blade flapping and stresses, and the effect on aircraft behavior, particularly during higher speed flight. The problem needs to be examined, and, if necessary, consideration should be given of various methods of gust locating angle-of-attack sensors in the blade itself or ahead of the blade.

The foregoing remarks are generally applicable to all types of helicopters. In the following, items peculiar to each of the shaft-driven configurations are presented.

10. Specific Concepts.

a. Single Rotor/Tail Rotor.

If this configuration were to be applied to the VHL helicopter, attention would have to be devoted to alternative methods of providing anti-torque, in place of relying on the conventional tail rotor driven from the main engine by means of shafting. One alternative system,

for example, might utilize separate, smaller engines to power the tail rotor. A dual-purpose thrust-producer might be used which would not merely provide anti-torque in hover but also additional thrust for forward flight. In addition, hydraulic drive for the tail rotor should be considered.

b. Co-axial.

The co-axial configuration appears to offer some promise for application to the VHL requirements. This arises from:

- A less complex transmission system, with the power being split into two paths in one unit, which directly drives each of the rotors.

- Considerable compactness, except for height, for the crane-type helicopter.

- A lower autorotational rate of descent, for the same disc loading, than for the single rotor.

Because the lower rotor operates in the wake of the upper one, problems may arise due to the resulting vortex interference. This interference could lead to increased noise and vibration levels and should be investigated carefully in any developmental program. There may also be some unfavorable rotor interaction in forward flight with this configuration. The lower rotor may experience higher alternating loads because of the uneven flow from the upper rotor.

For this configuration it was suggested that the use of a fixed collective, non-feathering blade portion inboard, together with a normally-controlled portion outboard, be considered. Auxiliary propulsion for forward flight could be used to reduce feathering requirements with consequent less mast tilt, causing the inboard sections to operate more efficiently.

In view of the lack of knowledge regarding co-axial helicopters, and the unavailability of suitably large test vehicles in the West, it is recommended that the feasibility of purchasing and testing of the Soviet twin-engine Kamov helicopter be studied.

c. Synchropter.

This approach may be considered a derivative of the co-axial in which the rotors are arranged closely side-by-side and intermeshed through use of negative dihedral. It is recommended that any large-crane study based on the co-axial configuration be expanded to include the synchropter, since the problems and advantages of both configurations are similar.

d. Tandem.

The following items specific to the tandem configuration were delineated by the subcommittee:

- Rotor overlap and gap should be carefully considered for the VHLH since it can produce significant noise and make the airloads unsteady.

- Convertible fan propulsion may offer a possibility of obtaining higher speeds with the tandem configuration.

- A yaw-control problem will exist with the tandem if hingeless rotor systems are employed, since differential lateral tilt is limited.

- Dynamic problems may be encountered on the VHLH because of the use of long interconnecting shafting between rotors. If the rotors are not overlapped, the possibility of eliminating this shafting by locating multiple engines at each rotor should be investigated.

- The long, slender fuselage of the tandem configuration may provide troublesome vibration. The judicious use of composite materials may help to solve this problem.

e. Lateral Twin.

The USSR has developed a very large lateral twin helicopter with an estimated gross weight of 200,000 lbs. While the lateral twin configuration is of interest, our experience with and knowledge of its characteristics are limited. Items which the subcommittee felt should be considered in such a design are as follows:

- The outriggers (or booms) are dead weight items and pose a dynamic structural problem.

- The download in hovering resulting from the outriggers could be reduced through the use of an open truss structure. However, the drag in forward flight might then be prohibitive.

- In forward flight, the rotors could be tilted, allowing an optimal fuselage angle.

- This configuration allows the fuselage to be relatively short, reducing the need for tail surfaces. The application of artificial stabilization to the lateral twin configuration may yield a reduction in the structural weight.

f. Tri-Rotor/Quad-Rotor.

Although limitations of time prohibited a lengthy discussion of these configurations, it was generally agreed that they could be of value for VHLH application. Airframe structural dynamics and drag problems exist for these concepts, as they do for the lateral twin. In addition, rotor interaction problems similar to those of the tandem configuration arise for the multi-rotor configuration.

SECTION III
TIP-DRIVEN HELICOPTER

The type of helicopter considered here is one in which the rotor is driven by a jet reaction applied at the tip. While this jet can be produced in several ways, principal consideration was given to the warm or hot pressure jet. Other configurations include the cold pressure jet, the tip-mounted turbojet engine, and a thrust producer mounted at the tip and driven mechanically or hydraulically from a powerplant mounted in the fuselage. It is felt that a helicopter utilizing a warm pressure jet of the 30-ton payload category could be readily obtained in the immediate future using existing technology. Although this would undoubtedly mean a major development program, there appear to be no major areas of technology to be developed in order to utilize a warm pressure jet for such an aircraft. There also appears to be little doubt that the VHLH can be achieved within the 1980-1990 time frame utilizing the tip jet drive.

1. Critical Areas for Development.

As in the case of the shaft-driven helicopter, one concern is with the low blade-passage frequencies. These may be even more critical for the tip-driven system because of the inherent limitation on the number of blades. In order to keep the gas velocity in the blade ducting below acceptable limits, the cross-sectional area of each blade must be relatively larger than the area of the blades of the shaft-driven rotor. This implies, for the same rotor solidity, that the jet-driven rotor will have fewer blades and hence a lower blade-passage frequency. The situation is further aggravated by propulsion efficiency considerations which may require lower tip speeds for the tip drive.

Another critical area to be examined is the precise determination of the yaw control power required for the tip-driven helicopter. Recent work indicates that one cannot simply design the tail rotor on the basis of anti-torque requirements. Control and engine-out requirement will dictate the design of the tail rotor to a much greater extent than for the shaft-driven helicopter. This in turn will influence significantly the geometry and weight of the fuselage.

Another critical area is that of getting precise weight estimations of components. The success of a VHLH design utilizing a tip-drive system, which appears to be competitive with the shaft-driven helicopter, will depend, to a large extent, upon the designer's ability to estimate accurately weights of such components as the rotor blades, the hub assembly, the gas producer (including the necessary ducting), and the fuselage.

2. <u>Recommendations for Specific Work.</u>

As for the case of the shaft-driven helicopter, it is felt that significant gains can be realized for the tip-driven helicopter, through the application of advanced material technology. Specific items here include the stages of the gas producer, the fuselage, and, of course, the rotor blades which must be capable of withstanding high-temperature gases while satisfying the strength and fatigue requirements imposed by the dynamic and aerodynamic loads.

In this latter regard, attention should be given to the jet flap. Not only is it possible to improve the maximum lift coefficient of the blade sections, but in addition the jet flap principle might be used to alleviate loads. One can visualize sensing systems on the blade, possibly electronic or fluidic, which would control the direction of the jet flap so as to affect a particular mode of vibration and, in turn, a particular vibratory response of the fuselage.

The problem of establishing criteria for the tail rotor design of the jet-driven helicopter was mentioned previously and is an area in need of more specific attention. The handling qualities of this particular helicopter configuration must be examined through the use of simulation and other methods to establish reliable specifications for the necessary yaw control power.

The large duct area required for the jet-driven rotor dictates a compromise between the external and internal aerodynamics of such a rotor. For this rotor one would like to employ an airfoil which is relatively thick but which has, nevertheless, a high critical Mach number coupled with reasonable stall characteristics. It is recommended that airfoil research be aimed specifically at developing section profiles which are optimized with respect to the jet rotor application.

3. <u>Recommendations for Component Work.</u>

Work on various components of the tip-driven VHLH should be started prior to the actual development of the complete helicopter. It is suggested that actual blade sections be designed, fabricated, and tested. Also ducting, seals, and by-pass valves should be built and tested. Testing of the powerplant could be performed by simulating the flow and pressure requirements imposed by the ducting, valves, tip cascades, and the aerodynamic torque of the rotor.

Although it appears possible to design a satisfactory warm/hot cycle rotor within the desired time frame, further investigation of materials suitable for use in rotor blade structure should be undertaken. Items to be considered include: (1) temperature effects;

(2) adjustment of fatigue strength and stiffness; (3) corrosion resistance; (4) fabrication techniques for very large, high-temperature blades; and (5) the effect of service conditions and environment on the strength of these new materials.

Elastic characteristics of tip-driven rotors should be investigated by both modeling and analysis. For example, it may be found that the thicker blade sections will allow departure from present practice with regard to the center-of-gravity and aerodynamic center of the section.

For configurations in which engines feed into a common duct system, consideration must be given to engine-out performance. Questions to be answered include the problems of backflow into the down engine and those presented by the requirement that the remaining engine operate at off-design conditions. This latter difficulty may be eased by the use of variable engine stators, variable geometry rotor nozzles, or separate ducting.

An investigation of methods of providing yaw control, and its drive system should be undertaken. Particular consideration should be given to the engine-out condition. Since the tail rotor is sized by control requirements rather than torque, the consequences of tail rotor failure are less severe than with shaft-driven rotor systems.

The autorotational characteristics of the jet-driven rotor should be studied. In autorotation the rotor acts as a centrifugal pump. This induced flow produces an added torque which must be overcome by the aerodynamic torque on the rotor blades.

The infrared signal emitted from the tips of the jet-rotor should be studied in an attempt to minimize it. Here, of course, the cooler the jet, the less the problem. The tip-driven rotor will, however, have a unique pattern due to the rotating tip exhaust.

4. Other Possible Configurations.

Consideration was given to possible ways of driving the rotor other than by conventional shafting. One such configuration which may hold some promise utilizes a thrust-producer of some sort mounted at the blade tip. This device is driven from a power source mounted in the fuselage, with the power transmitted by high speed drives through the rotor blades or high-pressure pneumatic drives. The latter will require a study of allowable operating temperatures and pressures.

The use of swivelling jets at the blade tips was considered by the subcommittee as one possible means of alleviating the blade droop problem at low rotational speeds. This problem, mentioned previously for the VHLH shaft-driven configuration, will also exist for the tip-driven configurations, although possibly to a lesser extent due to the thicker blades.

Another possible configuration utilizes separate jet-propulsion devices located inboard of the tips of the rotor blades. Such devices can be mounted on arms or blades separate from the main lifting blades. These propulsion devices can be directly connected to the main rotor and rotate at rotor speed or can be geared to the main rotor to rotate at other speeds as desired. The use of this system allows the main rotor blades to be designed without compromise from the ducting requirements. There are, of course, obvious penalties to be incurred with this system in the form of added weight and drag, and lower propulsive efficiency of such an arrangement. Past studies have not shown the idea to be too fruitful. However, this might change by the 1990 time frame.

The Chessman rotor, under investigation at Great Britain's National Gas Turbine Establishment, is another possibility. Here, circulation around a circular cylinder is maintained by means of a jet flap. This system provides a stiff blade which could circumvent many of the dynamic problems associated with the very large VHLH rotor. However, there are other problems, such as power-off operation, which must be resolved before this type of rotor becomes practical.

The cycloidal drive system is an interesting possibility for application to the VHLH. A sketch of the system is shown in Figure 1. Here, rotors are symmetrically placed on the tips of rotating arms. The rotors themselves can be powered and, in turn, can provide the torque to rotate the arms; or power can be supplied to the arms with the rotors autorotating. Such a configuration allows a large area to be swept with rotors of smaller diameter. Again, the increased drag and weight of the supporting arms offset the improved aerodynamic efficiency to an extent to be determined only by detailed design studies.

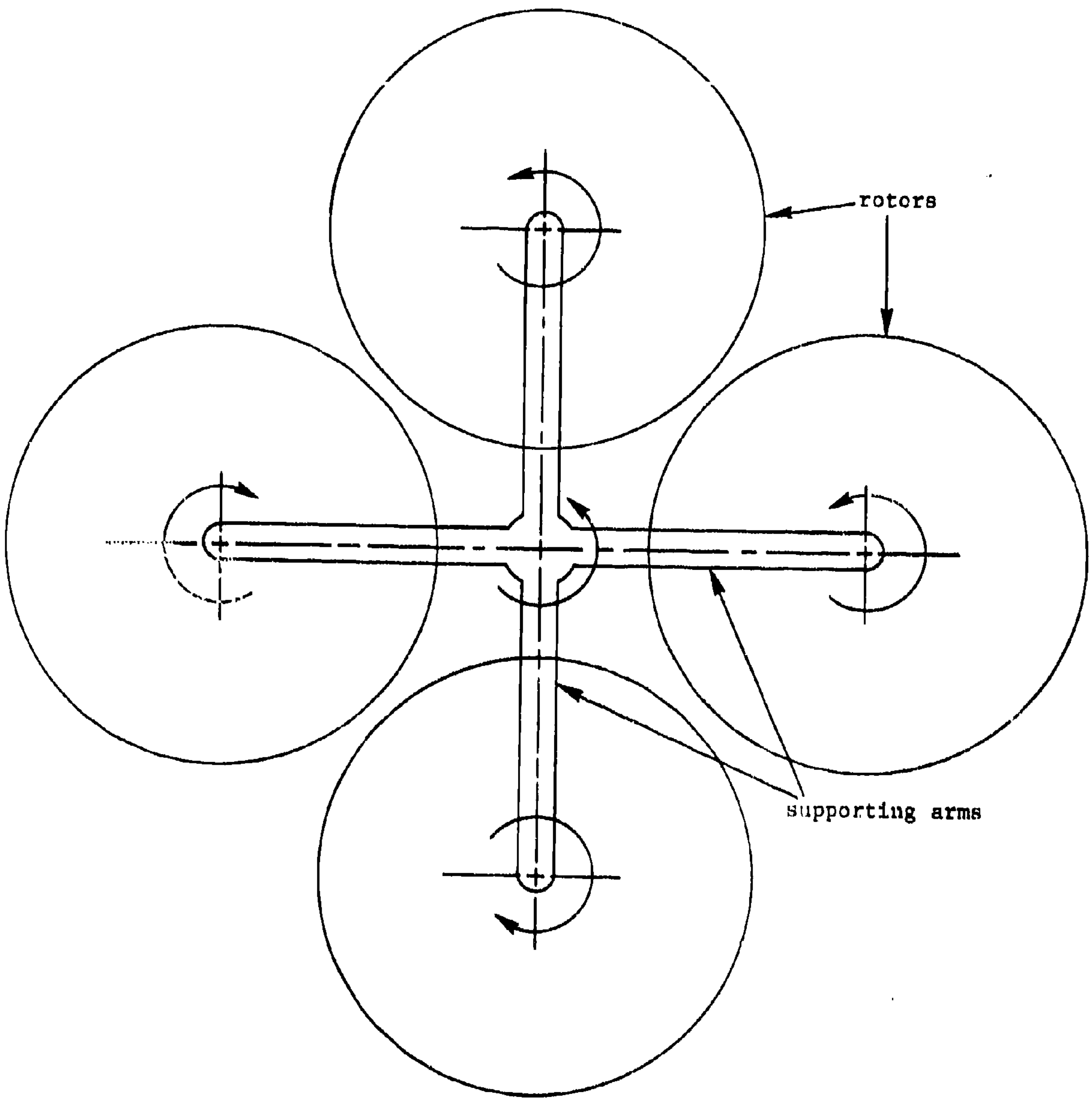

FIGURE 1

Cycloidal Drive

SECTION IV
POWERPLANTS AND TRANSMISSIONS

The deliberations of this subcommittee naturally overlapped to some extent those of the subcommittees considering the shaft-driven and tip-driven helicopters.

1. Engines.

Referring to the resource material in Volume III, the total required installed power for the VHL helicopter will be of the order of 50,000 shp. In the opinion of the subcommittee, today's technology can provide this power with high-cost development items from "off-the-shelf." This includes cold and warm cycle rotor systems, gas generators coupled to one or more remote turbines, and turbo-shaft conversions of existing engines. This last item will range from 10,000 to 30,000 shp, and could be ready for military qualification testing within three years. From the standpoint of the powerplant, it is felt that the Army could have a 50-60 ton payload helicopter much sooner than 1990 or that, by 1990, significantly greater payloads could be attained.

2. Transmissions.

The committee was of the same opinion regarding transmissions for the VHL helicopter. Current engineering and manufacturing technology can presently produce aircraft-quality transmissions with an output torque of 2.5×10^6 pound-feet. This is approximately the value of the torque required for the 50 ton payload helicopter.

3. Recommended Study Areas.

Although it was felt that existing technology could provide the required power for the VHL helicopter, the committee delineated several problem areas worthy of future study. The first area concerns the need to establish a valid power margin for the VHLH. This is with reference to the Army's current requirement of a 500 fpm vertical rate-of-climb OGE at a pressure altitude of 4000 feet and ambient temperature of 95°F. It is felt that a more direct specification of the power margin is needed. Considerable discussion of this point ensued in the general committee, without resolution. Apparently, the requirement of 500 fpm at 4000 feet and 95°F resulted from a world-wide survey of temperatures and altitudes. It provides a 95% probability of being able to operate in any part of the world, while providing some margin for maneuvering, gusts, and engine degradation.

Another area for study is the impact of methane fuel on engines. The subcommittee felt that the use of methane fuel may come sooner than the attention it has received suggests. The influence of methane characteristics on VHLH system design has not yet been fully evaluated. Special attention should be given to engine erosion protection. Erosion due to the ingestion of dirt, much of which is stirred up by rotor downwash, is a major cause of engine degradation.

The concept of an engine to be mounted on the tip of a rotor is worthy of further study; development would be a major undertaking. The engine must be designed to operate in a high G field. Rotor rotation also introduces gyroscopic forces on the rotating parts of the engine, fuel feed problems, and engine inlet distortion. All of these problems will of course impose additional requirements for test facilities.

It is felt that studies of vertically-mounted, complete engines, and vertically-mounted turbines separated from their horizontal gas generators should be continued. This latter configuration represents a possible way of transmitting power around a corner without the use of a gear box.

Although current technology will permit the fabrication of transmissions of the size required for the VHLH, there are certain problems relating to transmission design, fabrication, and operation to which attention should be devoted. One of these is the need for a stable, inert lubricant having a high Ryder rating. A goal of 5000 plus pounds per inch is desirable. Also, lubricants should be developed capable of higher operating temperatures, say 300°F. These two developments would contribute significantly to transmission technology.

Some effort should be expended to develop a transmission with an inert atmosphere. Such a design would avoid the adverse effects of oxygen which are present with today's transmissions.

Regarding the fabrication of transmissions, it is felt that there are large gains to be realized from developing diffusion bonding techniques. By such techniques, ferrous alloys, titanium, aluminum, and magnesium can all be more efficiently utilized in a transmission design. This is not to suggest that all four are necessarily to be combined in any one structural item, although this might conceivably offer certain advantages.

There is a need for developing foundry capability for casting very large, thin-walled transmission housing. Presently, technological constraint forces the designer to depart from more efficient designs in order to satisfy the casting requirements.

It is recommended that studies be continued on the configuration which incorporates mechanically-driven thrust producers near the rotor tip of very large rotors. In this configuration, the engine is mounted in the fuselage and drives shafts running out through each blade. The shafts, which are interconnected at the hub, drive open or ducted propellers mounted near the blade tips.

With regard to powerplant and transmission testing, it is felt that conventional helicopter transmission test time is too limited, at least with regard to the VHLH. Substantially longer testing is required and potentially will result in a cost saving by improving reliability, maintainability, and by accomplishing problem fixes early in the life cycle of the helicopter design. Retro-fits for a helicopter of this size will prove very costly. Engines, transmissions, and rotors should be installed in the aircraft and should accumulate at least 5000 hours of tie-down testing. While it is recognized that this is a relatively large effort, it is felt that this testing would be appropriate for any helicopter, and particularly so for the VHLH. This testing, which can be conducted concurrently with a flight-test program, is the type which is most useful in developing reliability and maintainability.

SECTION V
SUBSYSTEMS

The subcommittee on subsystems considered the following: cargo, control, avionics, crew station, airframe, and landing gear. The following observations, conclusions, and recommendations are directed only to those areas where the development of the VHLH requires new or refined technology.

1. Cargo Handling Provision.

The cargo handling system was identified as the area most demanding of new or improved solutions when extending current technology to 50-60 ton payload designs. Since the gross weight fraction for this system can be of the order of 5% (10% of payload), the first recommendation is that the requirement for the cargo hoist system be thoroughly examined. The principal questions requiring answers appear to be:

- Is a four-point system really required, or will a single hoist system combined with two two-point cross-bar systems be adequate? It is noted that 90% of current operations use a single-point lift.

- What length of cable will be required? Storage of conventional cables capable of carrying 50-60 tons will require very large drums. It is noted that the maximum cable length used to date in Southeast Asia is 90 feet, while the original HLH QMR called for 250 feet.

It is recommended that a thorough study to compare penalties and values of providing all the "desirable"cargo winching provisions be carried out before any firm requirement is established. More information is required concerning the downwash effects under very large rotors, and the way in which downwash may constrain hovering altitudes, before cable length can be finally determined.

A conventional cable system was deemed feasible, but drive, storage, and retrieval were identified as very cumbersome problems which could significantly affect payload efficiency and system reliability. It is recommended that a basic study be conducted to take a totally fresh look at all possible ways of retrieving and storing a load-carrying member, with special attention to the potential of fibre technology or flat cables. Drive systems different from the currently used hydraulic motors should be considered, with special attention to possible all-mechanical drives as an integrated part of the main transmission package. An accurate load measurement system is mandatory.

A major consideration will be the "man/machine interface" between the ground cargo handler and the hook or hoist capable of carrying and releasing 50-ton loads. Unmanned or automatically guided hookup systems may be required.

Load stability was also identified as a major problem area which could potentially limit the practical use of a 50-60 ton crane helicopter. Problems requiring further knowledge include:

- Load/airframe medium frequency dynamic coupling ("vertical bounce"). It was noted that with increasing size the airframe frequencies will approach the resolution frequency, and the pilot, located further from the center of the aircraft, will be more susceptible to any load/airframe oscillations.

- Low frequency "load oscillation/aircraft acceleration coupling" with single point loads. It is noted that even in current cranes this problem is not fully understood and apparently involves the pilot's inability to damp out large oscillations of single point loads, especially at night or under IFR conditions. This problem must be thoroughly understood so that the necessary response may be designed into the automatic flight control system to damp heavily any such phenomena.

- Accurate positioning. Precision hover, as well as load stabilization capability, must be provided to allow the pilot to position accurately very large loads. Accurate positioning could be accomplished either through the automatic flight control system or by flight director techniques. Any sensors used must be invulnerable to dust or sand entrained in the downwash. The system should be self-contained, although an option for control from the ground may also be required. It may be desirable to make provisions for multi-lift master/slave control capabilities in any automatic precision hover and load stabilization system.

- The vertical drag loads of very large payloads in the rotor downwash and the degree to which proximity of the ground plane relieves this download.

- The aerodynamic stability of very large objects, which in almost all cases are unstable.

- The dynamic load criteria for the objects to be lifted. (It was noted that in most cases sling points for ground-borne equipment are generally not designed to take airborne load factors and hoist-acceleration loads.)

2. Control Systems.

In addition to the automatic-control-system requirements for cargo handling discussed above, two major areas are of concern because of the very large system size under consideration:

- The need for total dependence on a fly-by-wire control system. The combination of the very heavy mechanical system that would be required in a helicopter of this size, the probable inability of providing in such a size the required degree of control "quality" (lack of deadband, slop, hysteresis, friction, elasticity, or sensitivity to airframe deflection), and the need for integrated, highly reliable, fail-safe, electronic unburdening facilities for cargo handling makes dependence on a full time, non-backed-up, fly-by-wire control system virtually a mandatory requirement. It was noted that design studies suggest weight savings of 2 to 3 tons in weight-empty by the use of fly-by-wire. To minimize the heavy penalty for control servos, the use of higher pressure hydraulic systems must also be considered, as soon as highly reliable, non-leaking, very high pressure technology is available.

- The kinesthetic environment of the pilot station and its effect on the pilot's ability to maneuver precisely and contain dynamic loads on other parts of the airframe. Current helicopter experience has already produced evidence that the pilot's control precision is affected by location relative to the normal axes of rotation and that his tendency to rotate the aircraft about himself can lead to excessive touchdown velocities. It was also noted that, in a hover, in order to hold a sling load motionless, the pilot will be forced to make any attitude correction about the load attachment station, thus exposing himself to the acceleration associated with his location away from this point. It is recommended that a systematic study of the effect of location on pilot reaction be carried out, initially using a moving-base simulation facility, but eventually in a variable stability flight vehicle.

3. Avionics System.

Apart from control requirements cited above, avionics system requirements do not appear to be unique, with the possible exception of the static discharge system. An analysis should be made to determine whether size effects will place any extraordinary demands on this technology. It is anticipated that fully developed, in-flight, fault monitor and maintenance diagnostic systems will be available to minimize the maintenance requirements of such large mechanical systems having the sophisticated control requirements discussed above.

4. Airframe System.

In multi-rotor configurations, the dynamic and elastic problems of very large airframes coupling two rotors together, in which basic fuselage modes must be separated from rotor excitation frequencies, represent, probably, the major development area associated with extrapolating to very large sizes; while in single rotor configurations, the dynamic/elastic characteristics of the longer blades required will be most demanding of advanced technology. In either case, basic work in composite material structural design technology, with particular attention to structural stiffness and internal damping, will be fundamental. This was mentioned previously as an area in need of study.

The sheer size of all components on a 50-ton vehicle will place extraordinary demands on built-in facilities for servicing, parts removal, and inspection. Attention to opportunities for breaking down components into modular elements which can be reasonably handled in the field is of paramount importance.

In addition to pilot, copilot, and load master, a flight engineer should be anticipated in the crew requirements. Landing gear technology is expected to be entirely adequate, although large size, controlled-pressure low-landing gears will be required for operations in unprepared areas.

SECTION VI
VTOL CONFIGURATIONS OTHER THAN HELICOPTERS

Rather than consider specific configurations of VTOL aircraft, the subcommittee viewed this class of aircraft as utilizing some sort of propulsor having a high disc loading. Other VTOL concepts which were considered were the lighter-than-air (LTA), and the Dynastat (a name derived from "dynamic" and "static" referring to a vehicle having the appearance of a very-thick, low-aspect-ratio wing). The Dynastat vehicle is inflated with helium and derives its lift from both dynamic and static effects. Various schemes for the Dynastat include horizontal fans for providing hover capability. These fans need supply only the thrust to balance the negative buoyancy of the system. "Multi-lift" refers to the concept of linking two or more helicopters together through some sort of a truss in order to lift a payload in excess of that which could be handled by an individual aircraft. In addition to those VTOL configurations which are technically feasible at the present time, more exotic possibilities for achieving vertical lift were considered. These schemes, though not feasible at the present time, may prove so in the future, with further advances in technology.

1. Problem Areas.

Problem areas which apply to the presently feasible configurations were identified by the subcommittee. The subcommittee's assessment of the magnitude of each problem is presented in Figure 2. The problems are rated as being very small (VS), small (S), medium (M), big (B), or very big (VB). For comparison purposes, the single helicopter is included in the table. It can be seen from this table that the only big problem which the subcommittee is seriously concerned about for the helicopter is in the area of aerodynamic and mechanical instabilities and vibrations. Concern for this problem is echoed by the other subcommittees. With the VTOL aircraft, there are several problem areas which must be resolved for application tc the VHL requirement, as can be seen from the table.

- Dynastat/Lighter-Than-Air. The Dynastat and LTA configurations are both attractive from a payload standpoint but have definite drawbacks in speed and handling qualities, the Dynastat to a lesser degree. While the pure LTA does not appear to be a likely candidate for the VHL mission, the Dynastat configuration may offer promise and should be considered.

- Multi-Lift. The basic problem with the multi-lift configuration is, of course, the coupling between the helicopters (or possibly even VTOL aircraft). What happens in the event of a power failure of one of the helicopters?

configuration / problem	heli-copter	VTOL	LTA	Dynastat	multi-lift
payload capability	M	VB	VS	S	M
downwash	M	B	S	B	M
30 ft. hover	S	B	S	B	S
ferry range	M	S	S	S	M
speed	M	S	B	M	M
power-off landing	S	B	S	S	B
aero-mechanical instability and vibration	B	S	VS	M	B
structural weight	M	M	M	M	M
handling qualities	M	M	B	B	B
gust sensitivity	S	M	B	B	B
noise	M	B	S	M	M

LEGEND: very small (VS); small (S); medium (M); big (B); very big (VB)

FIGURE 2

Summary of VHL Configuration Problems

The handling qualities of the multi-lift configuration, its response to a gust, for example, present another major problem. However, there is some promise of relief here through the application of a central automatic stabilization and control system tied in with redundant fly-by-wire controls in each helicopter. The central control system might even include a provision for sensing power failure of any of the component helicopters and thereby provide an automatic response to the emergency. Responses of this type are in need of detailed study; they might take the form of a quick release of the load or of a power reduction on the other helicopters.

- VTOL. The major problems with VTOL aircraft are all related to their high disc loadings, which result in the need for more installed power, in high downwash velocities, excessive fuel consumption in hover, and no autorotational capability. However, all of these problems could be alleviated, for the configurations which utilize open propellers, by the use of variable diameter rotors. Some discussion centered around the possibility of obtaining an increased ideal efficiency by expanding the rotor slipstream. One proposal to accomplish this expansion involves a lifting, wind-milling rotor mounted below the driven rotor. The merits of this concept were questioned, however, by some members of the AHWG. Additional analytical work is needed prior to serious consideration.

2. Other Means of Vertical Lift.

The possibility of obtaining vertical lift by other than aerodynamic or aerostatic means was considered by the committee. In particular, electromagnetic forces were mentioned as a possibility. It was generally agreed that, today, such devices, deriving their lift from a magnetic force field, serve only as interesting demonstration devices. However, by the 1990 time period, advances in technology may make them more attractive for practical application.

The subcommittee also considered two possible alterations to today's helicopter configuration which could have application to the VHL requirement. They felt that some consideration should be given to the design of a helicopter having a very low disc loading. The structural design and dynamic problem for the very large rotor will probably be difficult to resolve, but the potential power saving makes some effort at resolution worthwhile. Along these same lines, the flexible rotor, similar to a belt which can be wound around a reel, any have some promise.

Also considered was the augmented helicopter. Here, auxiliary jet or rocket engines would be used to provide additional thrust of short duration for vertical take-off at overload gross weights.

SECTION VII
SUMMARY OF ADVANTAGES AND DISADVANTAGES OF COMPETING VERY HEAVY LIFT (VHL) CONCEPTS

There are a number of ways of accomplishing the task of providing an aerial (VHL) capability, as covered in this report. Each concept discussed had inherent advantages and disadvantages associated with its specific design. These advantages/disadvantages are listed below, not for the sake of "ranking" the concepts, but only to summarize the issues associated with each particular concept.

1. Shaft-Driven VHL Helicopter (VHLH).

The predominant advantage is the bulk of actual field/service use which has been obtained utilizing designs incorporating shaft-drive systems. Other advantages include simplified control systems, as for the single rotor concept; shorter fuselage for the lateral twin and the synchropter concepts; smaller rotor diameters for any multi-rotor concept; elimination of the anti-torque rotor requirement for the tandem twin; lateral twin, and the co-axial; and specifically for the co-axial system, elimination of lift dissymmetry. Disadvantages also occur with any shaft-driven VHLH concept. These include, mainly, the size of the mechanical transmission required for the VHLH. Inherent to the shaft-driven concept include, for the single rotor, the size of the main and tail rotors; for the multi-rotor concepts, complex drive systems due to the requirement for synchronization of the rotors, and the dynamic problems of coupling two or more rotors together; for the co-axial system, control problems and rotor design to facilitate separation of the two sets of blades (thus increasing the overall height of the concept).

2. Tip-Driven (gas reaction drive) Helicopter System.

The major advantage is the elimination of the main rotor transmission, resulting in a significantly reduced vehicle empty weight. However, this weight reduction is offset by the increased specific fuel consumption of a gas-driven system when compared to a similar sized shaft driven helicopter. In addition, the larger cross-section of the gas-driven rotor blade required to accommodate the gas flow reduces the aerodynamic efficiency of the rotor system. Some reduction in rotor blade life should also be expected with the gas reaction drive system due to the temperatures of the gases flowing through the blades.

3. VTOL Concept (other than helicopters).

The major advantage appears to be that of forward speed and overload capability when operating STOL. Disadvantages include the high

disc loading associated with VTOL aircraft, resulting inefficient hovering capability, and increased noise.

4. Lighter-Than-Air (LTA) Vehicles.

This discussion will center only around the dynamic lift higher-than-air vehicle--that concept wherein the shape of the vehicle is selected to provide dynamic lift. The major advantages of this type vehicle lie in its large payload and extended ferry range capabilities. Noise for this type of system should also be somewhat lower than a helicopter. However, there are major disadvantages: inherently large size and vulnerability; more difficult handling qualities problems--maneuverability, gust sensitivity; and buoyance problems when operating at a reduced gross weight.

SECTION VIII
CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions of the Ad Hoc Working Group are:

1. A very-heavy-lift helicopter (VHLH), either shaft-driven or tip-driven is technically feasible today and could be type-classified by 1985.

2. The major technical problems appear to be excessive coning and droop.

3. Turbo-shaft conversions of existing turbojet engines suitable for a VHLH could be available within three to five years.

4. A modified lighter-than-air vehicle augmented with dynamic lift and lifting thrusters is a plausible concept.

It is recommended that the US Army:

1. Synthesize new component development and their testing for a very heavy lift helicopter.

2. Consider the feasibility of establishing a V/STOL test facility, possibly tri-service in scope.

3. Reexamine operational hover, engine-out and subsystem requirements for the very heavy lift vehicle with regard to avoiding non cost-effective requirements.

4. Study the modified lighter-than-air vehicle capability to fulfill the very heavy lift requirement.

5. Study the rotor downwash problem, from the point of soil stabilization, selecting the optimum disc loading for technical design considerations and from its effect on large bulky payloads (vertical drag loads).

6. Consider feasibility of purchasing (and initiating a test program of) the USSR twin-engine co-axial helicopter Ka-26 in order to expand the US knowledge of large size co-axial rotor helicopters.

7. Continue effort in airfoil research aimed specifically at developing section profiles which are optimized with respect to the jet-rotor application.

8. Continue investigations of alternate methods of yaw control and/or anti-torque, for large helicopters.

9. Continue studies of vertically mounted engines as a possible way of alleviating the transmission problem.

10. Initiate evaluation and development of concepts for retrieving and storing a load carrying member, with special attention to the potential of fibre technology or flat aerodynamic cables.

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13. ABSTRACT

An Ad Hoc Working Group (AHWG) was convened by the US Army Advanced Materiel Concepts Agency (AMCA) to consider the technical feasibility of developing a very heavy aerial lift vehicle to be operational by 1990. The mission spectrum for such a vehicle was assumed similar to the proposed QMR for the heavy-lift helicopter except for the payload requirement which was increased in these considerations to approximately 50-60 tons. Shaft-driven and tip-driven helicopter concepts were given major consideration. Powerplant and transmission development and problems relating to subsystems, such as load handling and control, were treated. Vertical take-off and landing (VTOL) concepts that were not high disc loading were discussed. Short take-off and landing (STOL) was not considered.

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